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STRESS CORROSION CRACK GROWTH RATES FOR ALLOY 82H WELDS

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Stress Corrosion Crack Growth Rates for Alloy 82H Welds

Background

Findings presented at October Meeting concerning SCC behavior of 82H GTA welds in 360°C water:

Maximum CGRs for 82H welds are similar to CGRs for 182 welds.

Flutter fatigue loading (R = 0.9, f = 1 cpm) does not significantly accelerate CGRs.

Large unbroken ligaments in wake of advancing crack front prevented accurate measurement of SCC rates by EPD or crack mouth opening displacement (CMOD) techniques.

Objective of Current Study

Characterize the SCC behavior of 82H welds at temperatures between 288° and 360°C.

Experimental Procedures

GTA welds fabricated by 3 vendors (“A”, “B” & “C”).

Tests performed on 0.6T CT specimens with cracks in both

- longitudinal [T-L] direction (ie, cracking direction parallel to welding direction)
- transverse [T-S] direction (ie, crack grows from root to crown)

Specimens were subjected to active loading

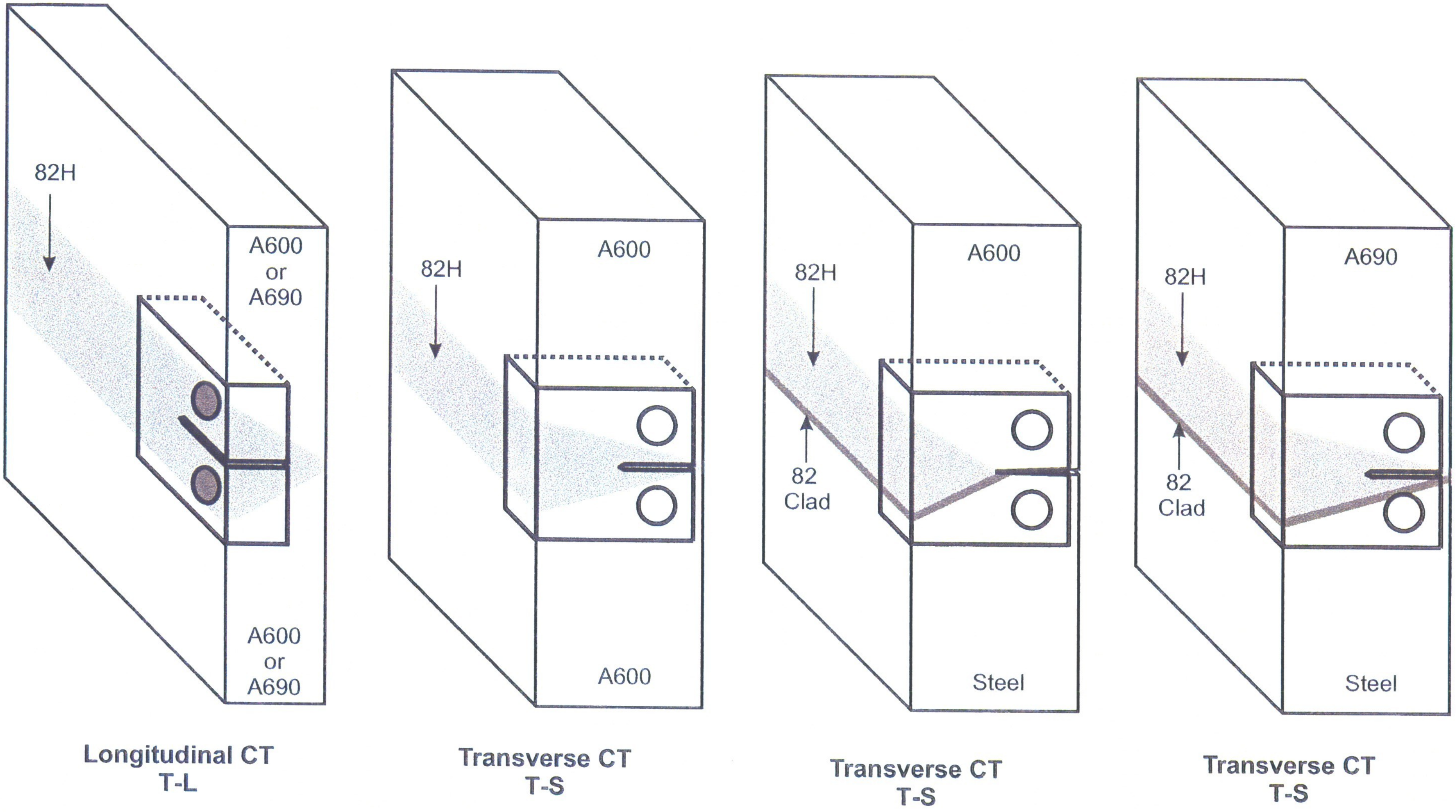
- Most tests were performed under constant load conditions.
- Limited testing was performed with
  - Unload-reload cycles (R = 0.65) every 100 minutes
  - Unload-reload cycles (R = 0.65) every 10 minutes
  - Fatigue flutter loading.

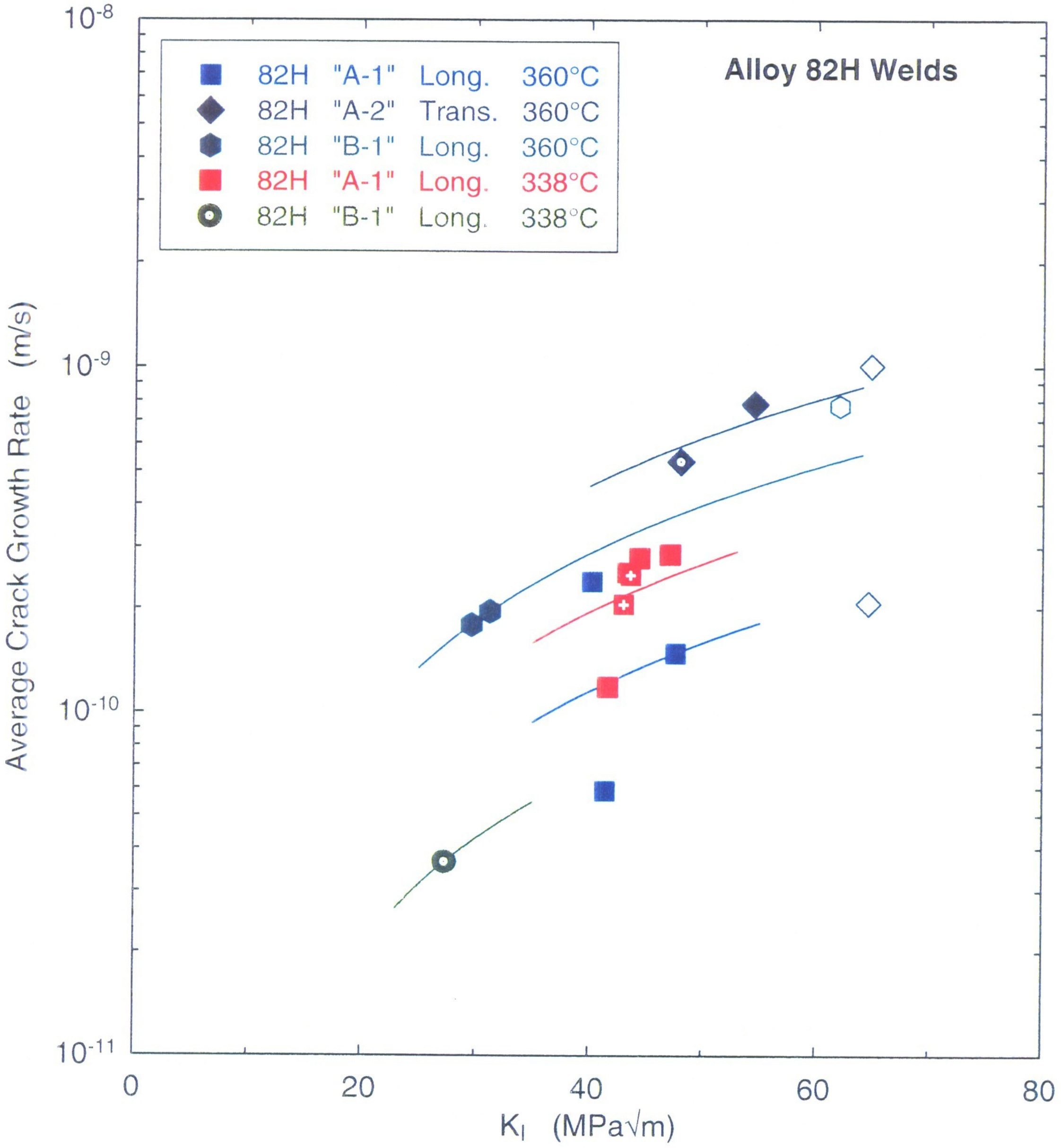
Test environment:

- Room temperature pH = 10.1 – 10.3
- 360°C tests were conducted in water with 150 cc H_2/kg H_2O
- 288°-338°C tests were conducted in water with 50 cc H_2/kg H_2O*

*except for 338°C flutter test of Weld B-1 which was conducted at 150 cc H_2/kg H_2O.

ORIENTATION OF WELD SPECIMENS



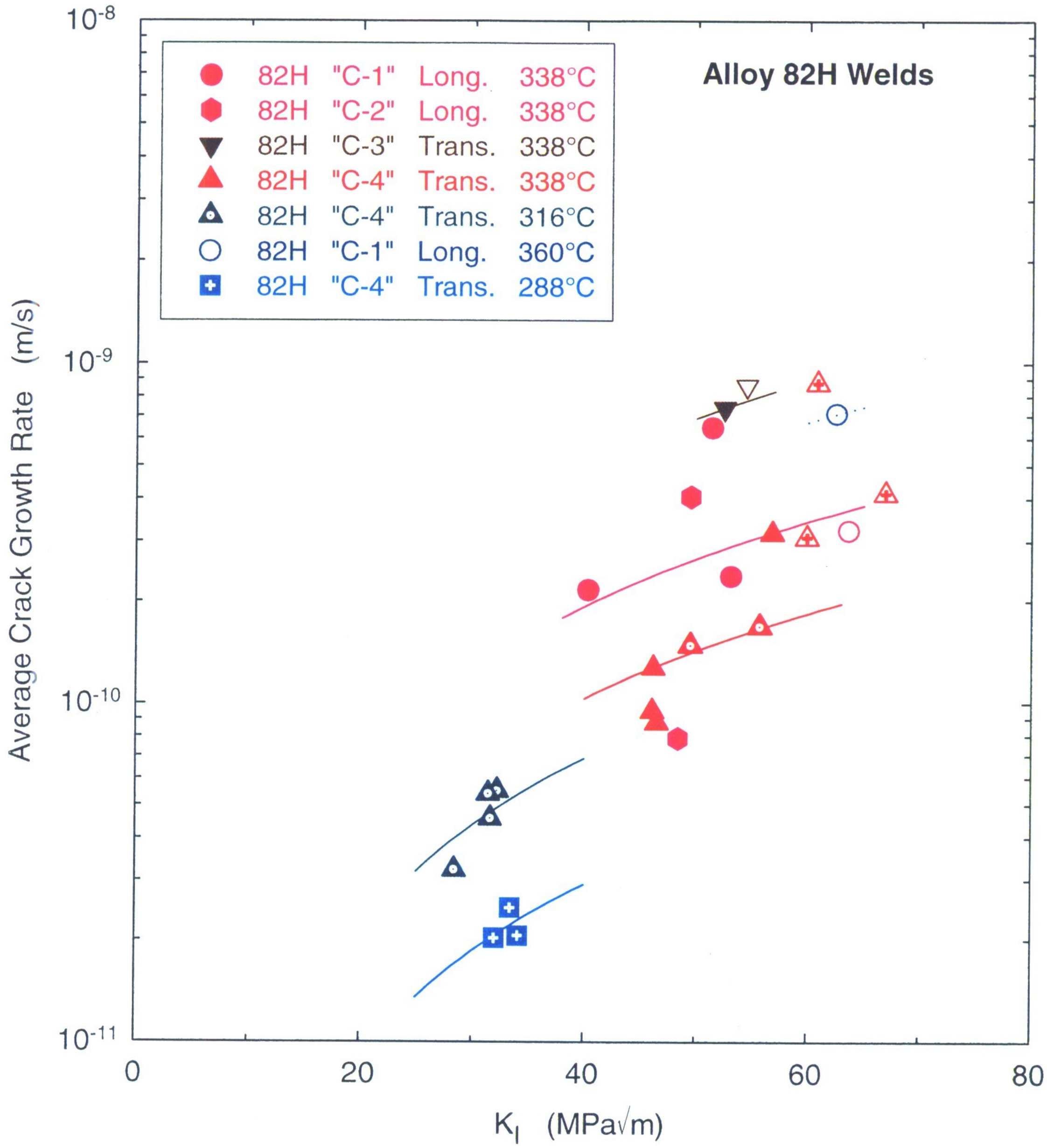


SCC Behavior of "A" & "B" 82H Welds at 338° & 360°C

- Scatter factor for a given weld is about 2X to 5X.
- Scatter factor for multiple welds is about 10X.
- On average, CGRs in transverse (T-S) direction are about twice those in longitudinal (T-L) direction,

  but there is considerable overlap in data.
- Periodic unload-reload cycles every 10 minutes do not appear to have a significant effect on CGRs for Weld A-1 (longitudinal) at 338°C.
- Fatigue flutter loading does not significantly accelerate CGRs for Weld A-2 (transverse) at 360°C.

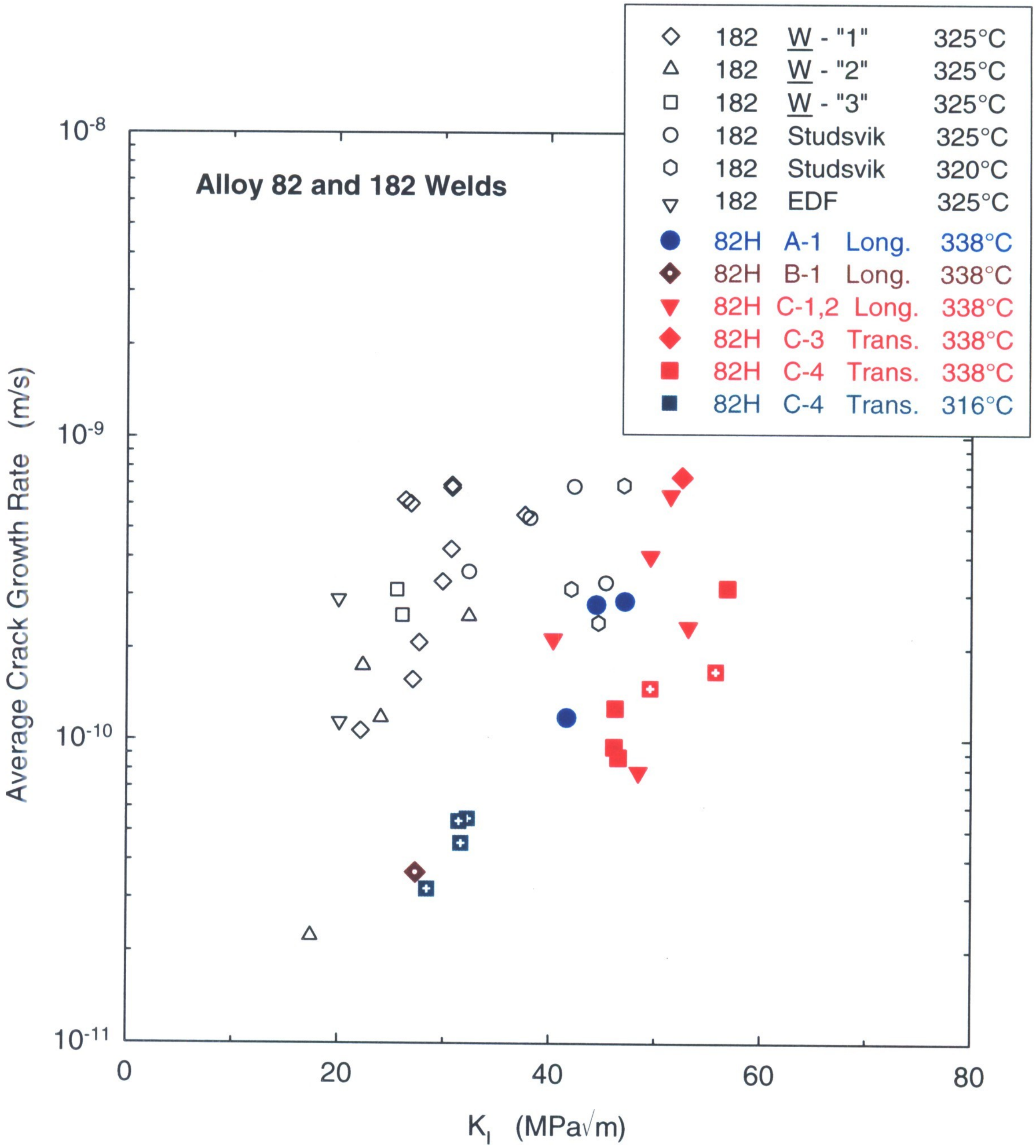
Open symbol denotes data points outside LEFM validity range.
Dot inside symbol denotes fatigue flutter loading (R = 0.9, f = 1 cpm).
Cross-hair inside symbol denotes unload-reload cycle every 10 minutes.



SCC Behavior of "C" Alloy 82H Welds at 288° to 360°C

- Scatter factor appears to be reduced by periodic unload-reload cycle.
- CGRs for longitudinal (T-L) direction [C-1, C-2] are
  less than CGRs for transverse (T-S) direction in one weld [C-3], and
  comparable to CGRs for transverse direction in another weld [C-4].
- Periodic unload-reload cycles every 10 minutes appears to increase CGRs by factors of 2X to 3X.
- Periodic unload-reload cycles every 100 minutes does not significantly affect CGRs.

Open symbols denote data points outside LEFM validity range.
Dot inside symbol denotes unload-reload cycle every 100 minutes.
Cross-hair inside symbol denotes unload-reload cycle every 10 minutes.



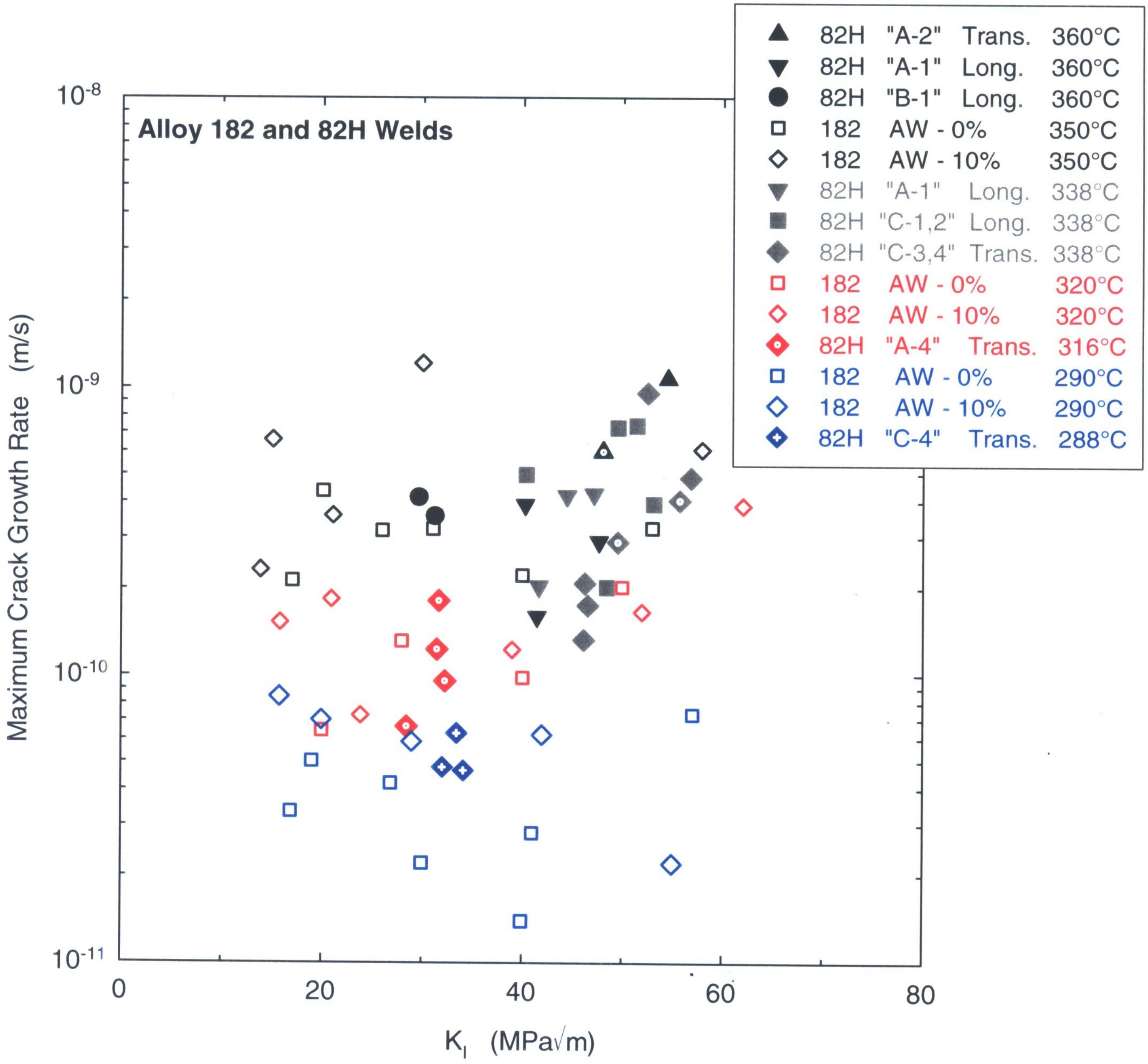
CGRs for 82H Welds in 316° & 338°C Water & 182 Welds in 320° & 325°C Water

(182 data from Bamford et al, 10th Internat'l Conf. on Environmental Degradation, 2001)

- CGRs for 82H & 182 welds appear to be similar at high K values.
- CGRs for 82H welds appear to be less than those for 182 welds in low K regime.

Dot inside symbol denotes fatigue flutter loading.

Cross-hair inside symbol denotes unload-reload cycle every 100 minutes.

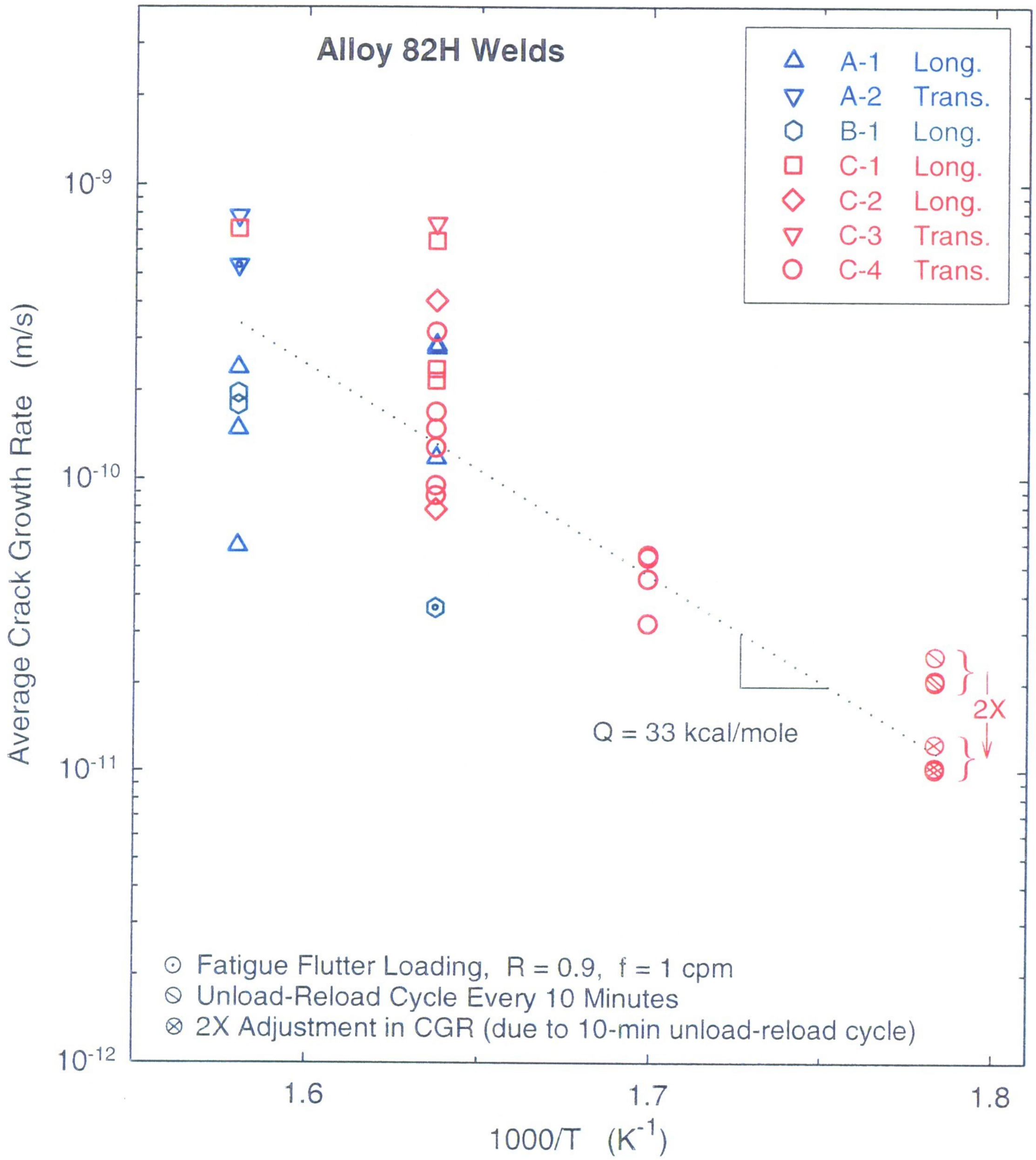


Comparison of CGRs for Alloy 182 and 82H Welds

(182 data from Le Hong et al, 10th Int'l Conf. on Environmental Degradation, 2001)

182 and 82H welds exhibit comparable CGRs at:
338°/ 350°/ 360°C,
316°/ 320°C,
288°/ 290°C.

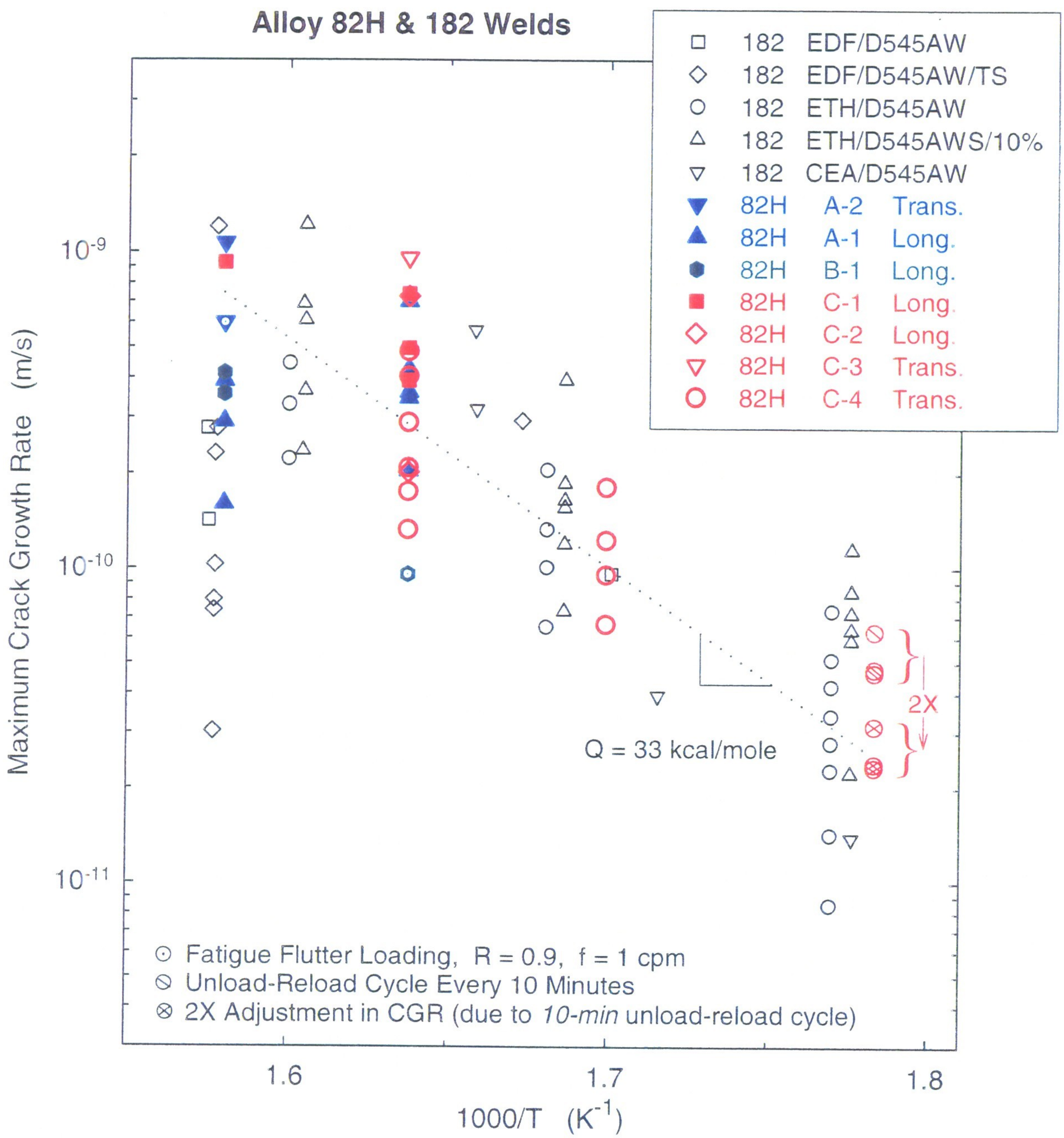
182 welds were tested in both as-welded and 10% cold worked conditions (10% cold work causes 2X increase in CGRs).
Cross-hair inside symbol denotes unload-reload cycle every 10 minutes.
Dot inside symbol denotes unload-reload cycle every 100 minutes.



Effect of Temperature on Crack Growth Rates for Alloy 82H Welds
(Equivalent CGRs at 40 MPa√m based on Scott model)

- CGRs exhibit an Arrhenius behavior.
- Data are consistent with an activation energy (Q) between 31 & 35 kcal/mole (130 & 150 kJ/mole)

Data points were obtained under constant-load conditions or with an unload-reload cycle every 100-minutes, except as noted by dot or slash.



Effect of Temperature on Crack Growth Rates for Alloy 82H & 182 Welds

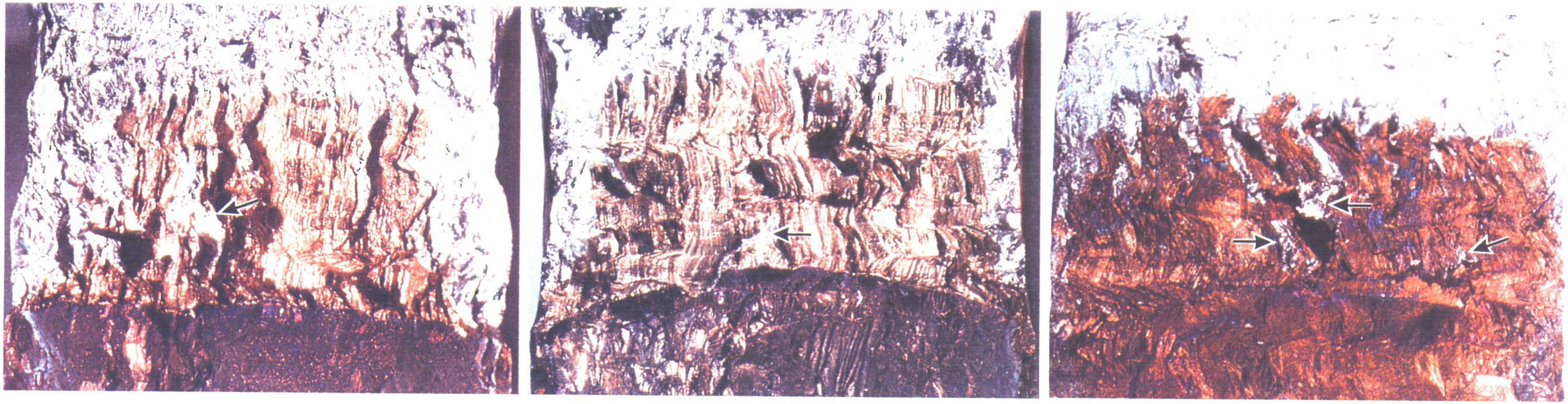
(182 data from Le Hong et al, 10th Internat'l Conf. on Environmental Degradation, 2001)

- CGRs for Alloy 82H welds are consistent with Arrhenius behavior exhibited by Alloy 182 welds.

  Data are consistent with an activation energy of 31 to 35 kcal/mole (130 to 150 kJ/mole).

  (CGRs were based on maximum crack extension values.)

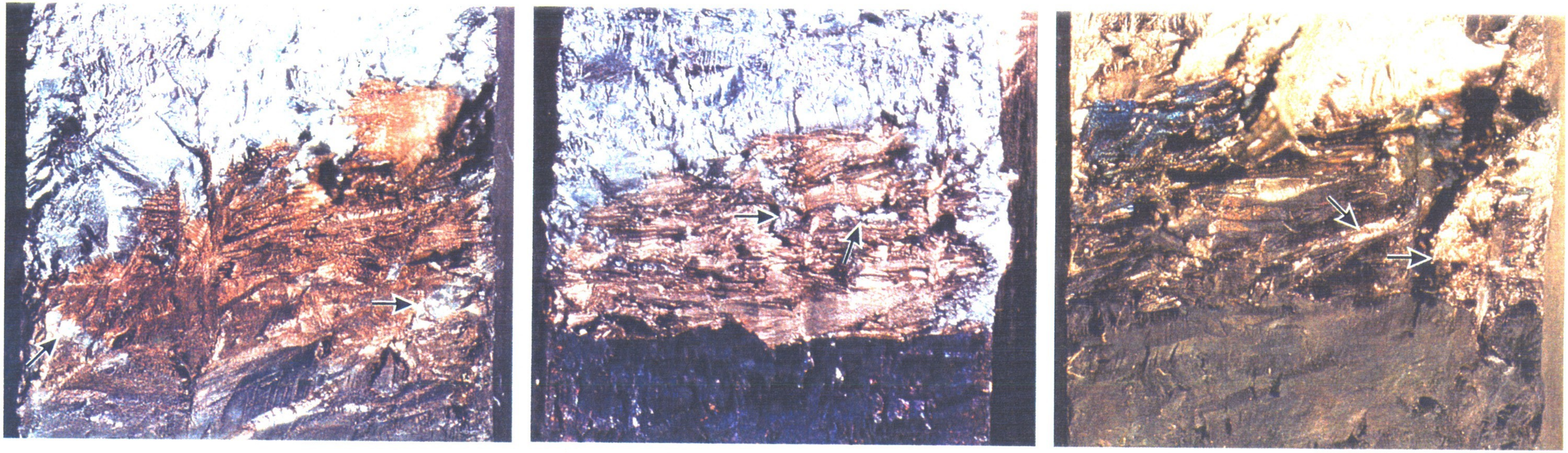
Alloy 82H Welds



Macroscopic fracture surface morphology for stress corrosion cracks propagating in transverse direction.

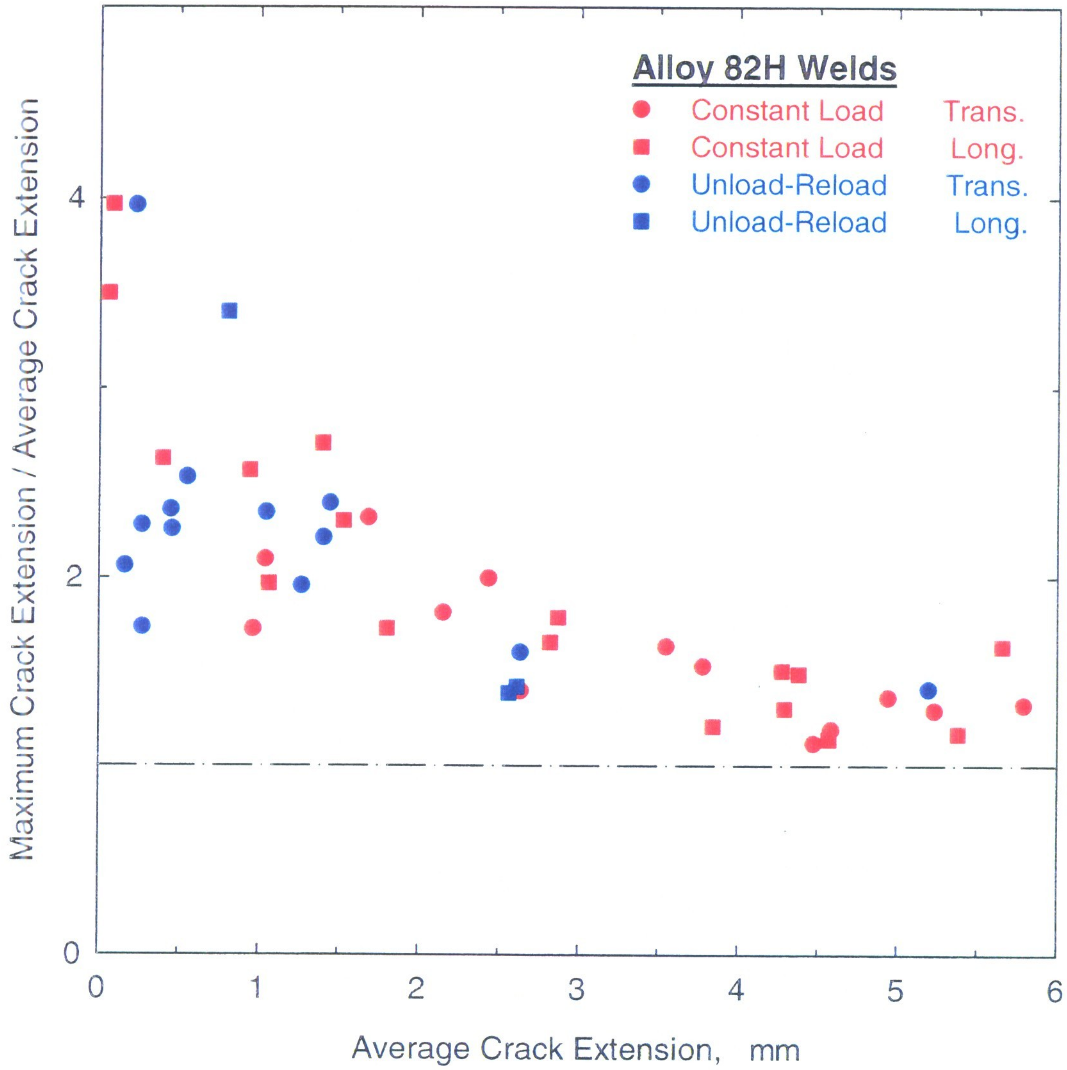
- SCC is typically uneven as cracking proceeds along favorably oriented dendritic grain boundaries.
- Note that unbroken ligaments (arrows) remain in wake of advancing crack front, even when crack extension is rather uniform.

Alloy 82H Welds



Macroscopic fracture surface morphology for stress corrosion cracks propagating in longitudinal direction.

Note that ligaments (arrows) remain in wake of advancing crack front, even when crack extension is rather uniform and there is 100% engagement of the precrack.



Maximum Crack Extension (Δa_{MAX}) v. Average Crack Extension (Δa_{AVE}) for Stress Corrosion Cracks in Alloy 82H Welds

- For $\Delta a_{AVE} < 2$ mm, Δa_{MAX} values are 2X to 4X greater than Δa_{AVE} values.
- For $\Delta a_{AVE} > 3$ mm, Δa_{MAX} values are 1.34 ± 0.16 greater than Δa_{AVE} values.
- Periodic unload-reload cycles appear to reduce difference between Δa_{AVE} and Δa_{MAX} at $\Delta a_{AVE} < 1$ mm,
  but has little effect at larger Δa_{AVE} values.

Stress Corrosion Crack Growth Rates for Alloy 82H Welds

Conclusions

Maximum CGRs for 82H welds are consistent with data for 182 welds.

> Differences in weld metal composition (82H v. 182) and welding process (GTA v. SMA) do not significantly affect CGRs.

CGRs exhibit an Arrhenius behavior with Q between 31 and 35 kcal/mol (130 & 150 kJ/mol).

CGRs in transverse (T-S) direction tend to be about twice those in longitudinal direction (T-L), but there is overlap in the data.

Unload-reload cycle (R = 0.65) every 100 minutes does not significantly affect CGRs.

Unload-reload cycles (R = 0.65) every 10 minutes caused a 2- to 3-fold increase in CGRs for weld "C", but had no significant effect on weld "A".

Scatter factors for individual welds tested under constant load range from 2X to 5X.

Periodic unload-reload cycles appear reduce data scatter.

Scatter factor for 82H GTA welds fabricated by three vendors is about an order of magnitude.

Unbroken ligaments behind crack front promote data scatter and preclude using EPD and CMOD methods to measure crack extension.

> Periodic unload-reload cycles appear to reduce extent of ligaments at low Δa.

References:

1. C. M. Brown and W. J. Mills, "Fracture Toughness, Tensile and Stress Corrosion Cracking Properties of Alloy 600, Alloy 690 and their Welds in Water," *Corrosion / 96*, Paper #90, NACE, 1996.

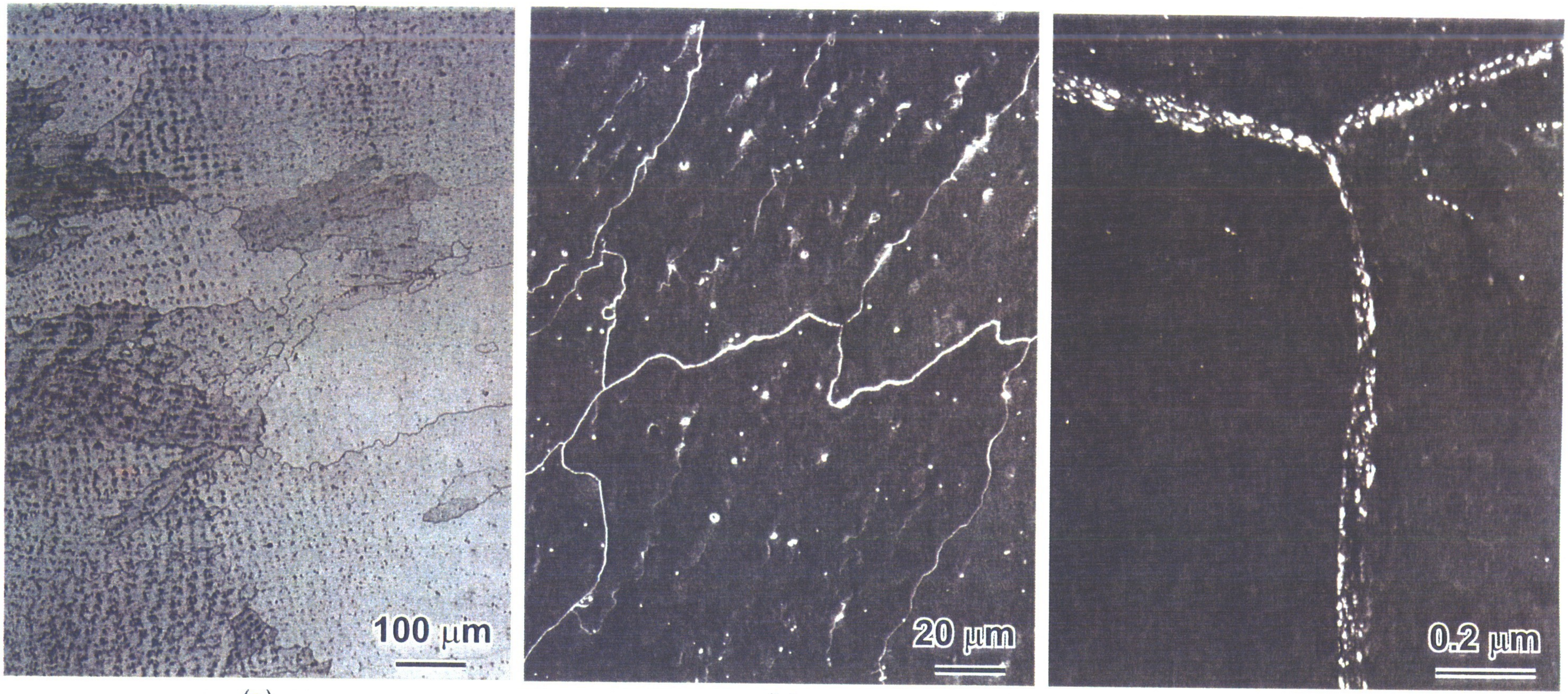
2. C. M. Brown and W. J. Mills, "Effect of Water on Mechanical Properties and Stress Corrosion Behavior of Alloy 600, Alloy 690, EN82H Welds, and EN52 Welds, *Corrosion*, Vol. 55, 1999, p. 173.

3. W. H. Bamford, K. R. Hsu, L. Tunon-Sanjur, J. Foster and A. McIlree, "Alloy 182 Weld Crack Growth, and Its Impact on Service-Induced Cracking in Operating PWR Plant Piping," *Tenth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems-Water Reactors,* NACE, 2001 (in press).

4. S. Le Hong, J. M. Boursier, C. Amzallag and J. Daret, "Measurements of Stress Corrosion Cracking Growth Rates in Weld Alloy 182 in Primary Water of PWR," *Tenth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems-Water Reactors,* NACE, 2001 (in press).

5. W. J. Mills and C. M. Brown, "Stress Corrosion Crack Growth Rates for EN82H Welds," Bettis Report B-T-3411, September 2001.

Alloy 82H Weld



(a) (b) (c)

Representative Microstructures Showing Dendritic Grain Structure in Alloy 82H Welds

(a) Light optical micrographs showing columnar grains with grain boundaries separating colonies of similarly oriented dendrites.

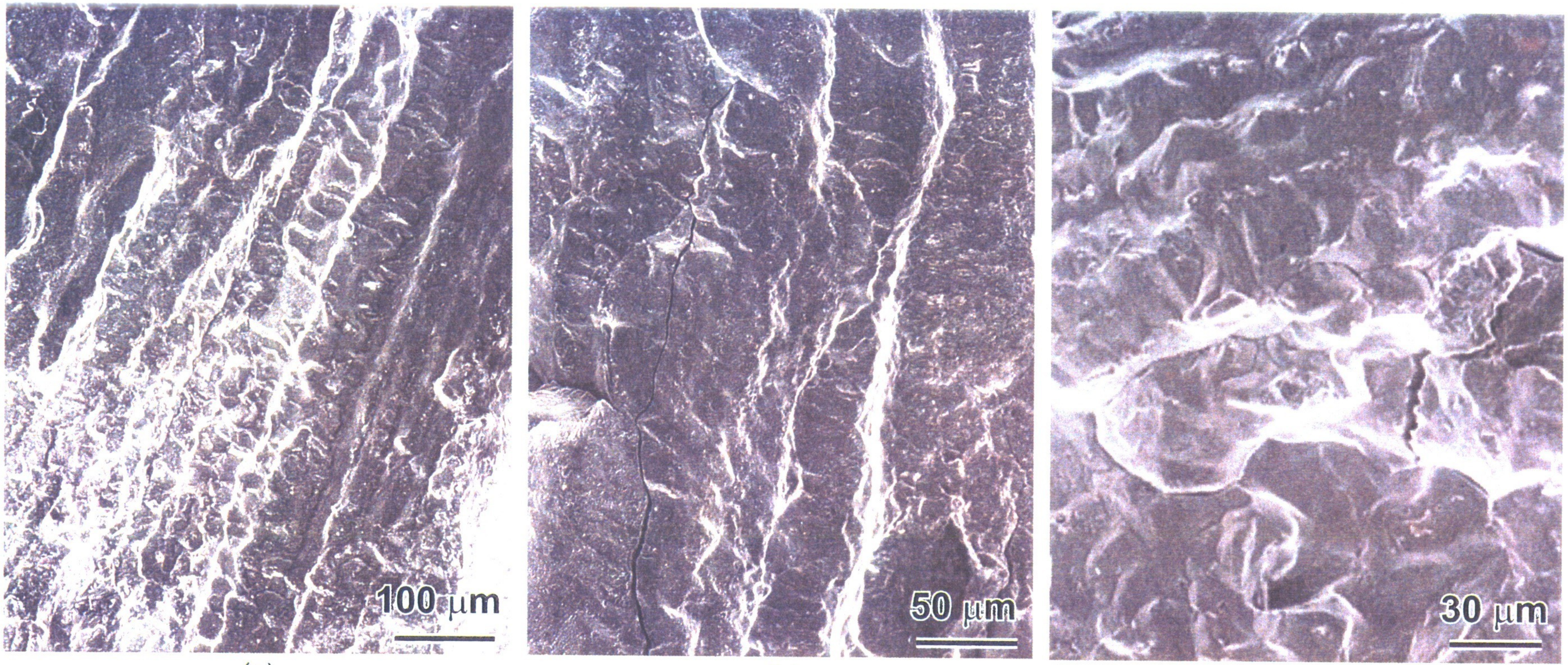
(b) Scanning electron micrographs showing undulating nature of grain boundaries, which is typical of as-welded structures.

(c) Dark-field transmission electron micrographs showing fine (3-16 nm) Nb,Ti(C,N) precipitates decorating grain boundaries.

Appendix

Microstructure and Fracture Surface Appearance for Alloy 82H Welds

Alloy 82H Weld



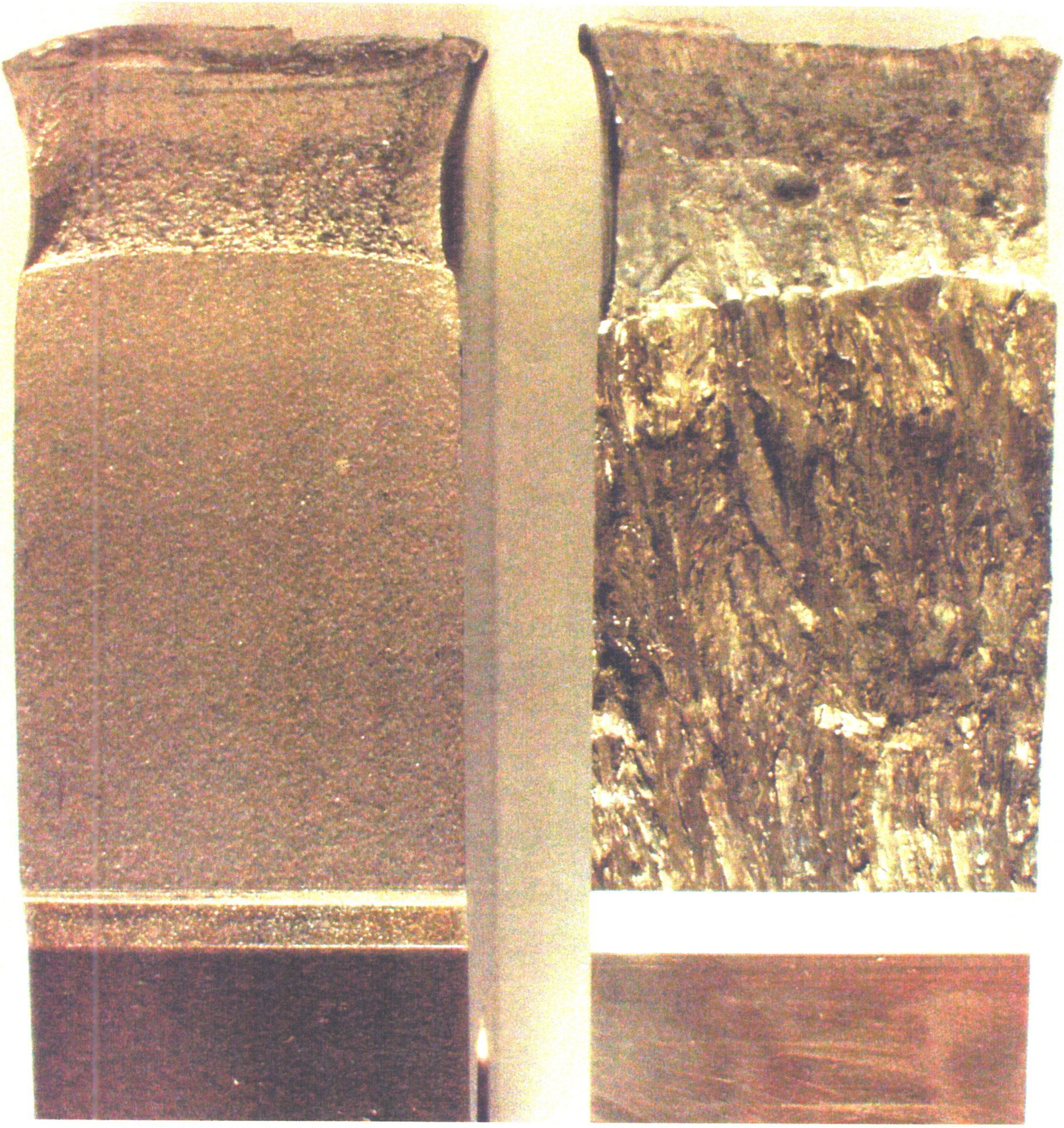
(a) (b) (c)

SEM Fractographs of Intergranular Stress Corrosion Cracks in Alloy 82H Welds

(a) Intergranular cracking morphology reflects dendritic grain structure. The undulating nature of grain boundaries in the as-welded condition gives rise to the wavy intergranular fracture surface.

(b) Intergranular SCC in the transverse direction.

(c) Intergranular SCC in the longitudinal direction.

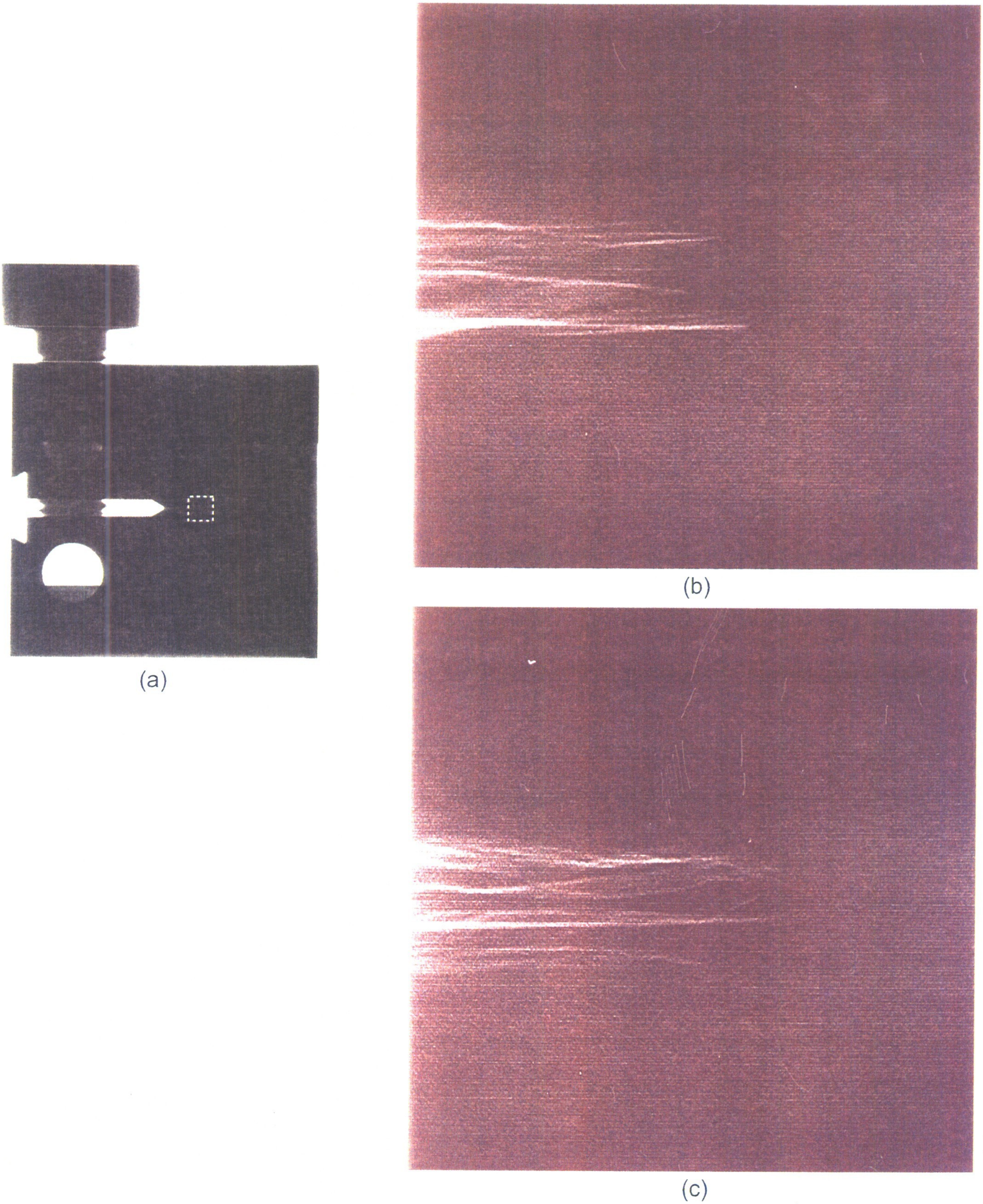


(a) (b)

Fatigue Fracture Surfaces

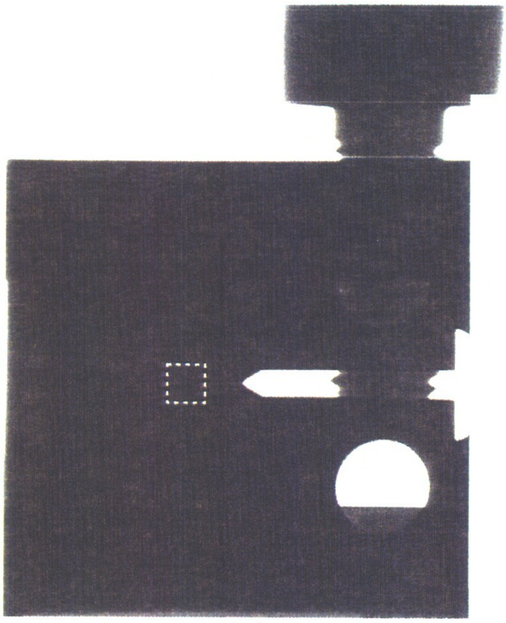
(a) Alloy 600. Fatigue fracture surface is smooth and planar.

(b) Alloy 82H Weld. Fatigue fracture surface is very rough and non-planar, reflecting the dendritic nature of as-welded structure.

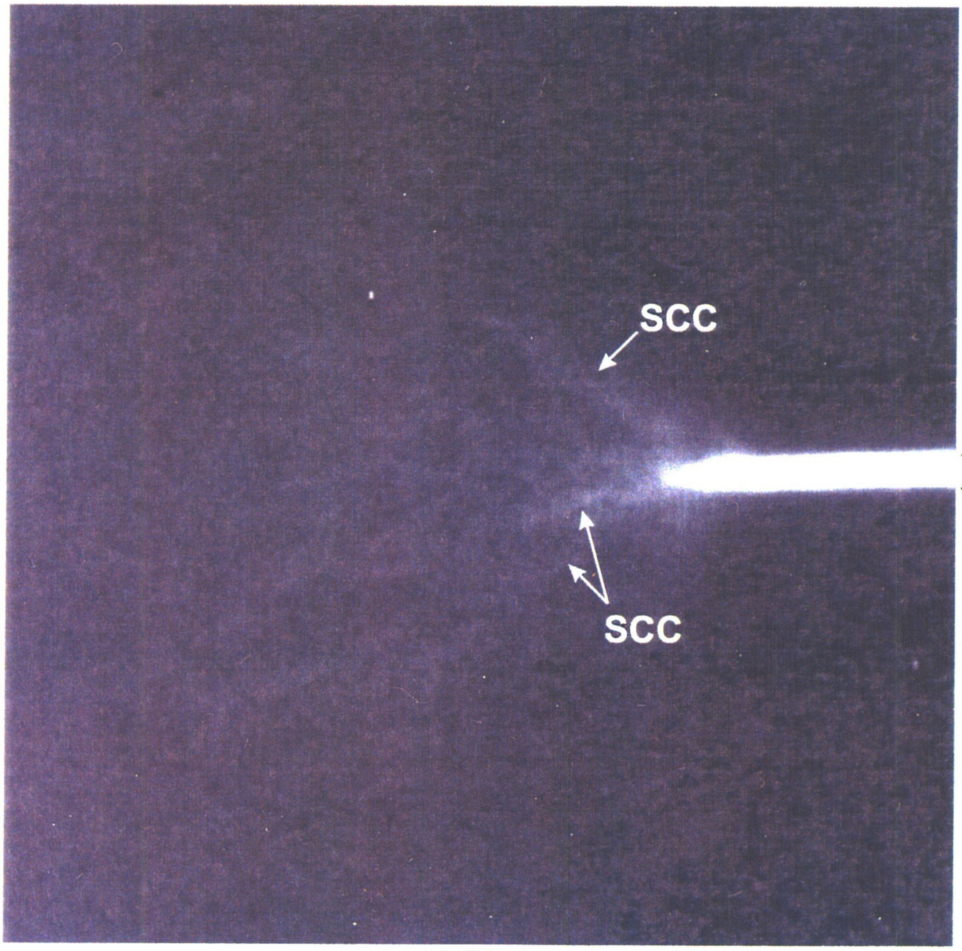


Microfocus X-ray radiographs showing non-planar nature of fatigue precracks in bolt-loaded CT specimens of Alloy 82H weld.

Nonplanar nature of fatigue precrack (even when crack front is uniform) affects incubation of stress corrosion cracks.



(a)



}← Fatigue Precrack

(b)

Microfocus X-ray radiographs of stress corrosion crack emanating from fatigue precrack in bolt-loaded CT specimen of wrought metal.

Note that fatigue precrack has a sharp, planar morphology, whereas stress corrosion crack appears to be diffuse.